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THE SCIENCECRAFT PROCESS

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Abstract

In this paper, the authors propose a new process for the development and operation of unmanned vehicles for the exploration of space. We call the vehicle *Sciencecraft* to distinguish it from the more traditional vehicle *spacecraft. A Sciencecraft is an integrated unit that combines science instruments, electronics, telecom-mu nications, power, and propulsion elements into a single system.*

The sciencecraft process begins with the formation of a single integrated team of scientists and engineers. This team's first task is the definition of science objectives and measurement requirements. An observational sequence is then designed to minimize conflicts in observing times. Once the observational sequence has been established, an integrated sensor system can be designed. This is an iterative process that generally results in refinements to the measurement requirements and observational sequence. The end result is a self-sequenced integrated payload that takes maximum advantage of the principles of *shared functionality* and *shared redundancy.* This new approach has been made possible by emerging technological capabilities now at hand, especially by the advent of new dense-packaging and low-power electronics. Because this process integrates both science and engineering requirements from the very start, it will result in the maximum science return for the mini muTn investment of resources.

We illustrate the power of the sciencecraft approach by describing the success of the Planetary Integrated Camera Spectrometer (PICS), an integrated sensor system in which the "sciencecraft" process has been applied to the development of a single subsystem, which integrates multiple functionalities. PICS is a case-in-point where the sciencecraft process has been successfully demonstrated.

We then describe a sciencecraft mission for exploration of the outer Solar System, including flybys of Uranus, Neptune, and an object in the Kuiper Belt. This mission, called the Kuiper Express, is an example of how the sciencecraft approach can return "Voyager class science at ten cents on the dollar. "

1. The Sciencecraft Concept

In this paper, we propose a new process for the development and operation of unmanned vehicles for the exploration of space. We call the vehicle *Sciencecraft* to distinguish it from the more traditional and familiar *spacecraft*. *A Sciencecraft is an integrated unit that combines science instruments, electronics, telecommunications, power, and* propulsion *elements info a single system.* This new concept has been made possible by recent advances in technology, especially by the advent of new dense packaging, low power electronics, and lightweight integrated instrument systems. These capabilities lead to the integration of function, lower mass, lower cost and a shortened development cycle.

The key to the sciencecraft concept is the new process by which missions are developed. This is illustrated in Figure 1. A sciencecraft mission begins with the formation of an integrated mission team of scientists and engineers. This team's first task is the definition of science objectives and measurement requirements, leading to the definition of a critical data set. An observational sequence and the conceptual design for an integrated sensor system are then agreed upon. Only after the sensor system is defined is the design of the sciencecraft hardware subsystems begun, e.g., the computer, the telecommunication, the power and propulsion subsystems and the integrated thermal and structural design. This is an iterative process in which cost/schedule considerations are introduced often resulting in refinement of the measurement requirements and observational sequence. The end result is a self-sequenced integrated payload and vehicle in which the hardware is matched to the observational Requirements and non-functional redundancies are minimized.

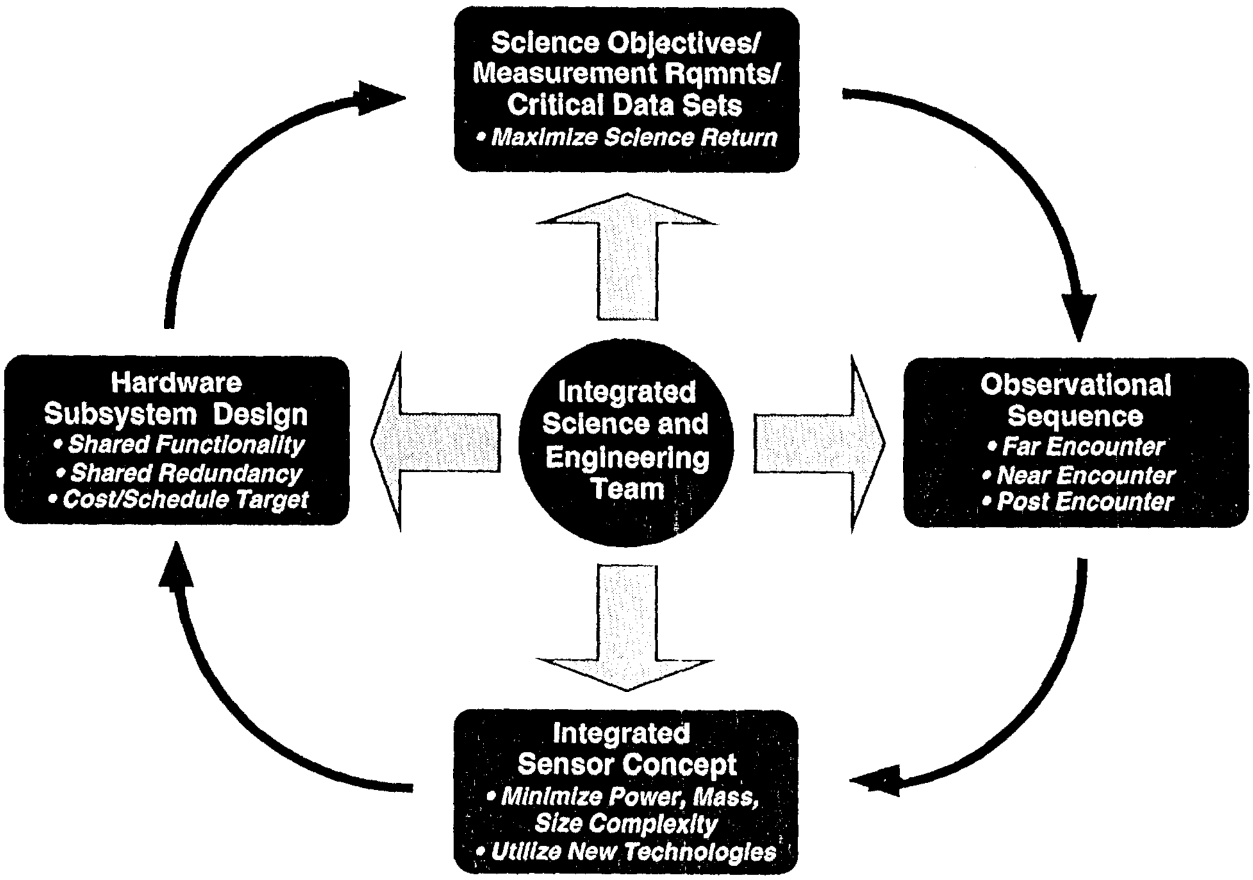

Figure 1. The Sciencecraft Process.

This approach is in sharp contrast to the traditional approach of mission planning in which a spacecraft and its. component subsystems are frequently designed before the instrument payload is selected. A comparison of the traditional and sciencecraft approaches to mission development is presented in Figure 2. As this figure illustrates, the traditional modularized approach to the development of a spacecraft becomes reflected in the modularity of the organization of the project. Individual instrument, spacecraft subsystem, anti mission design teams are formed, leading to undefined interfaces and unshared redundancies, both between instruments and between the instrument teams. However, in the development of a sciencecraft, the vehicle and mission are designed as a totality. An integrated design team jointly addresses all science and engineering issues. The makeup of the team is chosen so that all relevant disciplines are represented. However, in the design process, the team members are strongly encouraged to go beyond the confines of their own expertise. And they are instructed to view with abhorrence the adoption (or rejection) of an approach or idea simply because it was (or was not) invented at their home institution.

A sciencecraft is designed with several major objectives in mind, including the following.

Rapid Access to the Entire Solar System. The detailed design and fabrication of a sciencecraft must take less than 36 months from inception to delivery for launch. Any point in the Solar System can be accessed in less than a decade after launch, even the Kuiper Belt, lying beyond the orbits of Neptune and Pluto. [1]

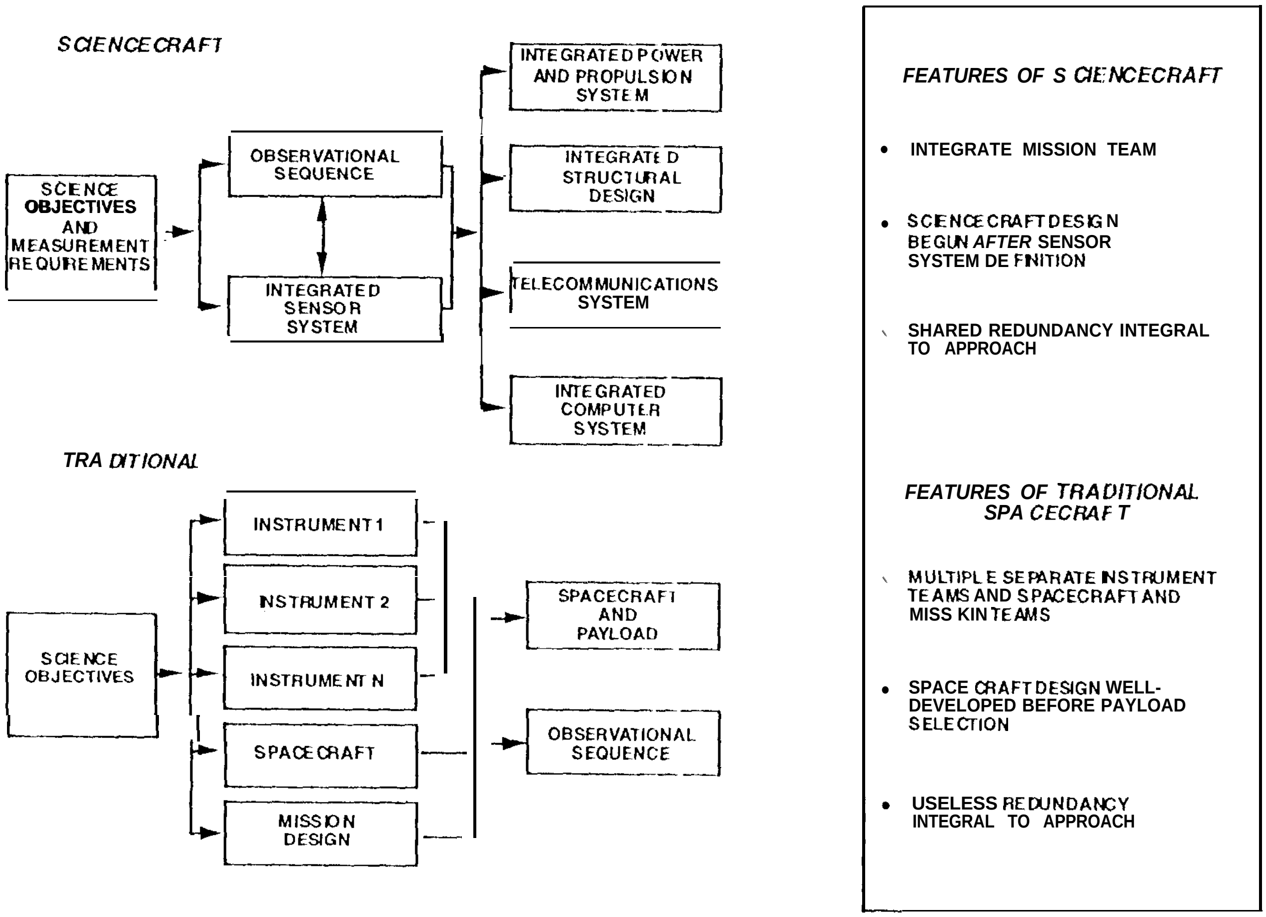

Figure 2. The benefits of the. sciencecraft approach to mission development are shown and compared to the characteristics of the traditional approach.

Low Development Cost. The cost of the detailed design, fabrication, and launch of the first sciencecraft is consistent with the $150M limit set by the NASA Discovery Program, This cost reduction is achieved in several ways. A single integrated mission team replaces multiple separate instrument, spacecraft and mission design teams. Shared redundancy and functionality replace separate and isolated redundancies for each subsystem. The reduced mass of sciencecraft permit the use of smaller, cheaper launch vehicles, Reduced electrical power permits the elimination of costly nuclear technology, even for missions to the outer Solar System.

Low Mission Operations Cost. During the long cruise phase of a mission the sciencecraft will be "space-stored" in a spin-stabilized mode. Ground operations will provide monthly checks of sciencecraft health. High-performance miniaturized computers will permit increased levels of autonomy. Navigation, sequence generation and checking and execution may be performed on-board, reducing the need for ground-based operations during gravity assist flybys and target object encounters.

High Science Bandwidth. It is not necessary to reduce science capability when developing low-cost missions. Sciencecraft instrumentation can meet or exceed the science yields of previous missions. For example, the Kuiper Express may yield a Voyager-class science yield, while costing an order of magnitude less. The sciencecraft will use integrated instruments; The example mission is based on the Planetary Integrated Camera Spectrometer (1'1(3) instrument, which was developed to demonstrate that a science payload consisting of a visible imaging camera, an infrared spectrometer, and an ultraviolet spectrometer is achievable within the mass, power, and cost constraints of the Pluto Fast Flyby mission.

Higher Reliability. The unshared hardware redundancies, inherent in the traditional approach to spacecraft development, will be replaced by shared redundancies increasing sys(cm-level reliability. Consider a suite of four separate instruments. Each has a complete set of electronics but none of them can tolerate a failure, For the integrated case wc provide multiple, redundant units at lower cost, mass and power consumption and yet have *higher* system-level reliability.

Low Mass, Power, and Size. The extensive usc of dense packaging electronic technology, the use of new high-efficiency solid state power amplifiers and the usc of solid-state switches reduce mass and lower energy requirements to permit the operation of the sciencecraft on the limited solar power available in the outer Solar System, with an entire vehicle operating on as little as 1(1 watts of electrical power.

No Nuclear Power. All primary electrical power for a sciencecraft is supplied by solar power, even for missions to the Kuiper Belt (i.e., out to about 45 astronomical units (AU) from the Sun). The use of solar power at these considerable distances is made possible by the use of large solar panels, by advances in solar electric technology that address the problems of operation at low temperature and under conditions of low illumination, by innovative thermal and energy management, and by the use of low-power electronics technology. The use of solar power eliminates the need for costly nuclear alternatives. The use of solar power also eliminates radiation damage to instruments by neutrons from the RTGs.

Solar Electric Propulsion. Although it is not inherent to the sciencecraft approach, the emerging technology of Solar electric propulsion (SEP) may prove to be of great benefit in sciencecraft missions. SEP engines use solar power to provide a low thrust over an extended period of months to years. The high specific impulse (-3000 see) provided by SEP enables planetary missions using small launch vehicles. SE]' can be used once the sciencecraft leaves earth orbit to shape the trajectory and add impulse. SEP provides effective thrust to distances of 3–5 AU from the Sun and has been shown [1] to be especially capable of shortening the time required to reach any target object in the Solar System to five years or less. In addition, the use of SEP in the inner Solar System is synergistic with the use of solar power in the outer Solar System, because both require the deployment of solar panels with extremely large collection areas.

11. PICS: A "Sciencecraft" Success

The Planetary integrated Camera Spectrometer (PICS) is an integrated sensor system in which the "sciencecraft" approach has been successfully demonstrated [2]. in this section, we summarize the design and prototype development of PICS as an illustration of the power of the sciencecraft approach.

PICS is a sensor system that combines the functions of four optical instruments often deployed on planetary missions: a near-infrared spectrometer, a visible imaging camera, a visible spectrometer, and an ultraviolet spectrometer. The integration of these functions has served to minimize the mass and power required to produce these data types, while yielding a data set optimized for correlative analysis.

The design of PICS was based on a set of observation] sequences for the UV, visible, and IR channels, for the flyby of a hypothetical outer Solar System object. A single sensor system was designed, housing all four channels, with shared redundancies in the integrated electronics. This integrated approach improved reliability and resulted in substantial cost savings in manufacture, integration, test, and mission operations.

To achieve the necessary level of hardware/software integration, PICS was designed to support an "integrated timeline," that is, one in which data collection is optimized when the channels are operated in a time multiplexed fashion (Figure 3). This allowed the development of a highly integrated instrument in which only one of the four channels would collect data at any one time. The single signal chain (with a completely redundant, powered-off signal chain available for increased reliability) reduces the power required to run the detectors. integration of the observation sequence design will reduce mission costs and enable mission planners to make the greatest use of the few precious hours of the target object flyby and avoid the sequencing problems encountered on earlier missions, such as Voyager and Galileo.

Figure 3. Integrated PICS timeline for an encounter of Pluto/Charon.

From the outset, the PICS team sought to simplify the system as well as to minimize the mass and power of the instrument by maximizing the level of its integration. New technology and innovative design were! introduced leading to major improvements in capability. Wherever possible, the instrument's four channels would use common optics and electronic signal paths. For example, a single primary mirror was used for all wavelengths, avoiding the need for duplication of this high mass element. All structural and optical elements were made from Silicon Carbide (SiC), for high stiffness, strength, and low thermal expansion. Miniature, densely-packed electronics were used, reducing mass and power.

PICS was developed in partnership with several industrial team members, 'l'he CCDs were provided by Loral of Milpitas, CA. The infrared focal plane assembly was developed at the Rockwell Science Center of Thousand Oaks, CA. The structural configuration of PICS, developed in collaboration with SSG inc. of Waltham, Mass., is shown in Figure 4. 'l'he telescope has a triangular shaped optical bench housing the three highly integrated optical systems. The triangular construction offers leverage in achieving a lighter and stiffer optical bench, in which the off-axis telescope optics (except for the primary mirror and sunport pickoff mirror) and detectors can be conveniently integrated and aligned externally. This design assures ease of manufacture, integration and test, which in turn will help control phase C/L) costs.

At this writing, the PICS structure and optical components for the visible channel have all been fabricated and successfully tested. A modified version of PICS designated MICAS has been selected for space demonstration on New Millennium Program flight DS-1, scheduled for launch in 1998.

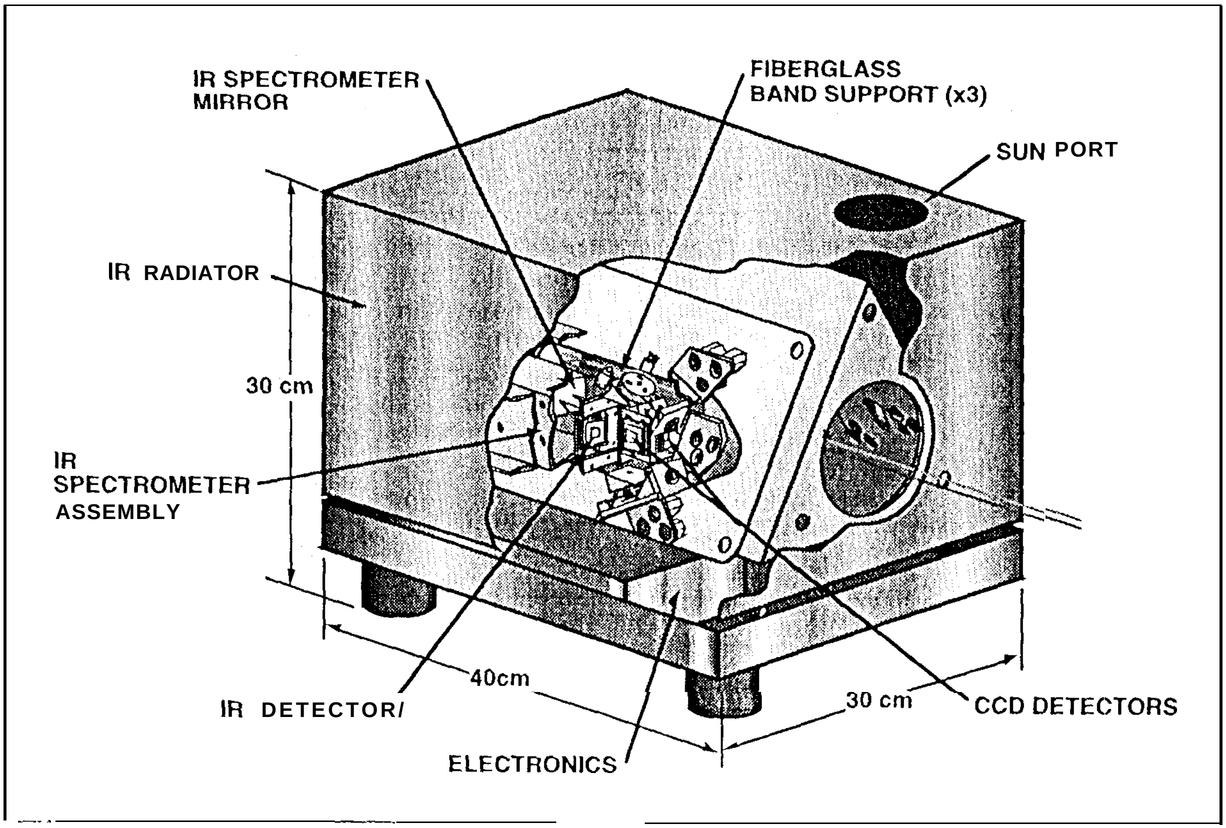

Figure 4. Structural configuration of the Planetary Integrated Camera-Spectrometer, PICS, viewed from the IR spectrometer side.

III. The Kuiper Express Sciencecraft

The Kuiper Express is a concept for a deep space mission in which the sciencecraft approach has been successfully applied. A team of engineers and scientists from J])], and industry was formed in the Summer of 1994 to study the feasibility of developing a science craft to perform an initial reconnaissance of the Kuiper Belt. They called the craft (and the mission on which it will be sent) the *Kuiper Express,* in honor of the astronomer Gerard Kuiper, who was the first to realize that a population of comets must exist beyond the orbit of Neptune as a remnant of the formation of the planets. They have termed it the *Express* because of the relatively short time it will take to arrive at the inner edge of the belt, reaching the orbit of Neptune (at 30 AU) only ten years after launch. An extensive discussion of the Kuiper Express science objectives and mission description is presented in a companion paper[3] being given at this conference.

The Kuiper Express will utilize the sciencecraft approach, as described in Section I. Accordingly, an integrated mission study team was formed and has defined the a set of science objectives. These science objectives imply a set of measurement requirements. The study team then developed an observational sequence based on the postulated flyby of a 500 km diameter Kuiper Belt object by the Kuiper Express Sciencecraft. The purpose of these observations was to obtain a complete coverage of the sunlit face of the target object in each of the four instrument channels at the highest resolution possible. The team found that a closest approach distance of 1000 km optimized this data set. The critical data set is recorded in the final hour before closest approach, anti the volume of this data set is about one gigabit,

Once the sensor system and the observational sequence were defined, the study team focused on the design of the sciencecraft hardware subsystems and the subsystem architecture. Several requirements followed immediately from the above definitions and the parameters of the on-board subsystems were defined. We now take the reader through a description of these.

The major features of the overall sciencecraft architecture were dictated by consideration of the extremely low "ambient" temperature in the Kuiper belt. Objects residing there and relying on only the feeble rays of the Sun for heat will find their temperature fallen to 80K or less. Since the sciencecraft electronics will must be maintained at a temperature of about 270K, it is necessary to define a *Sciencecraft Core* of temperature critical elements and place them in a thermos bottle. The dissipation of the electrical power required to operate these elements keeps the sciencecraft core at about 280K, even in the Kuiper Belt. To keep the sciencecraft core from overheating during the early part of the mission, when the craft is closer to the Sun, it is connected by temperature controlled variable conductance redundant heat pipes to a 1000 cm^2 radiator. When the craft passes beyond 3 AU from the Sun, the heat pipe! fluid freezes out and thermally isolates the inside of the thermos. The PICS optics and detectors are separated from, but attached to, the thermos. Heat transfer through the supports and flex pivots maintains the temperature at 150K for these elements. The sciencecraft core is illustrated in Figure 5.

The sciencecraft on-board propulsion system uses solar electric propulsion (SEP) rather than the more familiar chemical propulsion system. The decision to use SEP was made to minimize cost and to allow the use of a Delta II launch vehicle rather than needing a Titan, Atlas or Proton. The use of SEP results in a fully fueled sciencecraft having a mass of about 800 kg at the time it leaves Earth orbit, which permits the use of a Delta launch vehicle. The use of chemical propulsion to conduct the same mission would require the injection from Earth orbit of a craft of over 6000 kg mass and would require a much larger launch vehicle (e.g., a Titan or a Proton). The SEP propulsive system provides the capability of processing 380 kg of Xenon propellant at a specific impulse of over 3000 seconds. It will operate more-or-less continuously for 31 months after launch. When the Kuiper Express Sciencecraft reaches a distance of 3 AU from the Sun, the SEP system will have expended its fuel and will be beyond the range where the Sun can provide sufficient power. It will then shut clown.

The use of SEP in the inner Solar System meshes well architecturally with the use of Solar power at the Kuiper Belt, for both require the use of large Solar arrays. The Solar arrays will be designed and built by the Boeing Corp. under contract to Olin Aerospace Corp., with whom we are teamed for this effort. They will be 64 m^2 in area and provide more than 15 kilowatts at 1 AU. This is more than sufficient for running the SEP thrusters. They will provide 8.5 watts at 40 AU, sufficient for thermal and attitude control and data playback. The pointing of the solar panels toward the Sun must be to ±4°. The Boeing Corp. has long experience in building Solar arrays for use in space and has conducted tests, which have validated performance under the conditions of 10W7 temperature and illumination they will experience at 40 AU from the Sun.

Attitude control is performed in three different modes. During SEP powered flight, the sciencecraft will be three-axis stabilized, using the gimballed SEP thrusters themselves for thrust vector control. Gas thruster backup will be available during this phase. Attitude control during unpowered flight (i.e., after SEP shutdown) will use spin stabilization at ~0.03 RPM during the long cruises phases of the mission and three-axis stabilization using gas thrusters during encounter. A Sun tracker and star sensor will be used to define the sciencecraft orientation at all points in the mission. During SEP powered flight, attitude control is needed at an accuracy of ±1°. During the three-axis stabilization for data collection, attitude control of the craft will be accurate to ±4°, with fine pointing of the sensor accurate to ±5 μrad/sec via a gimbaled target tracker, While spin stabilized, attitude control will be accurate to ±0.2° during data playback for antenna pointing toward the Earth; otherwise, during cruise spin stabilization will be ±2°, allowing less frequent maneuvers.

'1 'he Integrated Computer System (ICS) will be a fully redundant dual string system. The ICS will be based on the JPL,-designed Advanced

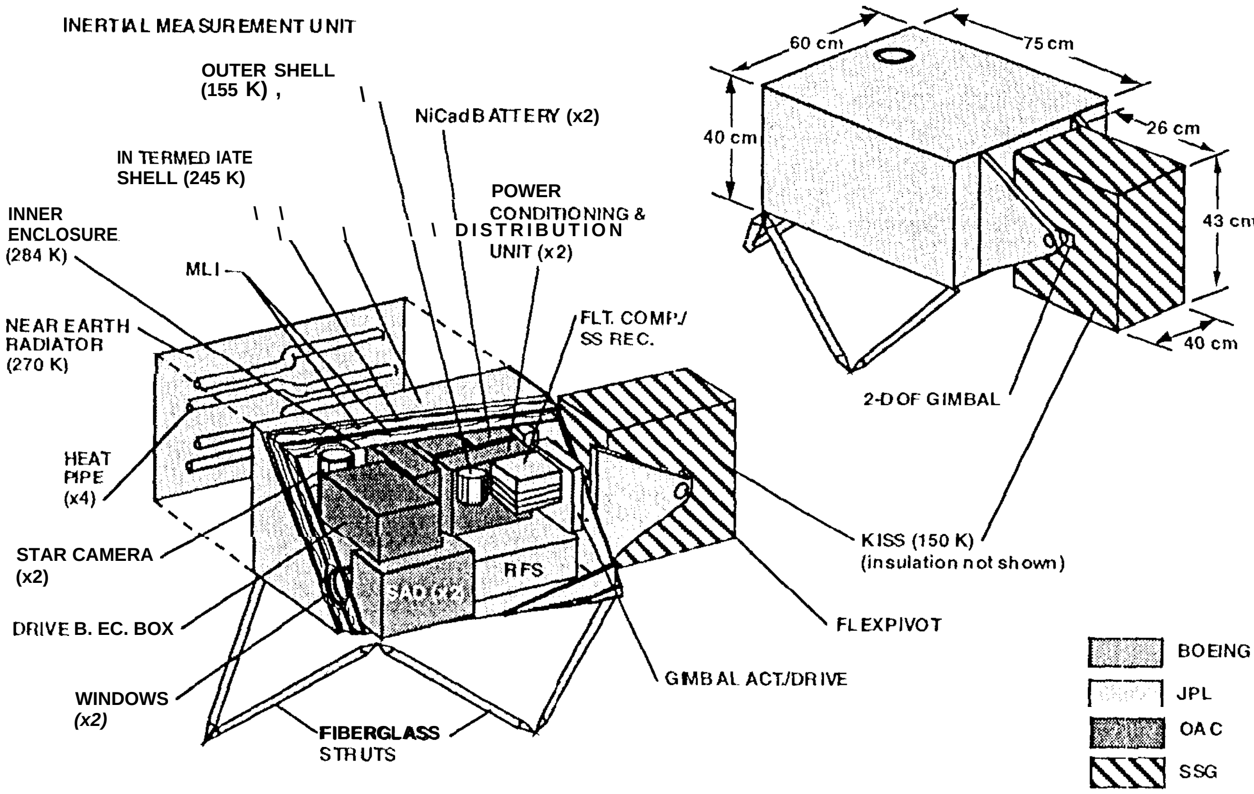

Figure 5. Schematic drawing of the Sciencecraft Core illustrating the high level of system integration.

Flight Computer (AFC) Module.[4] The AFC has a 32-bit architecture and is built upon new high density packaging technologies, including multichip module (MCM). The ICS also incorporates technologies for MCM stacking, and die stacking for memory. The ICS will have a mass of less than 2 kg and during normal operation will consume one watt of electrical power running at clock speed of 0.5 MHz, and deliver about 0.5 MIPS performance. It will be interfaced to dual DRAM-based solid state recorders, each having a one gigabit capacity and consuming 0.5 watts of electrical power when in use. The ICS will perform on-board sciencecraft operation, housekeeping and data management functions. Depending on mission requirements and limited only by electrical power, the ICS will be capable of operating at clock speeds of up to 25 MHz, consuming about 10 watts, and delivering a performance of about 20 MIPS. This reserve capability could be used to enable real-time science data compression, on-board science data analysis, and autonomous sciencecraft operation during periods of increased activity, e.g., during a planetary encounter.

The sciencecraft telecommunications system will use X-band transmission for command uplink and sciencecraft and science data retrieval. There will be three on-board antennas, one high-gain and two low-gain. The low-gain antennas are omni-directional patch antennas and will be used for routine sciencecraft health checks while within a few AU of the Earth. The high gain antenna will have a diameter of 2.3 meters, the largest non-deployable antenna that will fit inside the shroud of the Delta launch vehicle, and will be primary for all communications at distances greater than 3 AU. We plan to use the X-band solid state power amplifiers developed under the NASA New Millennium Program. For data playback to the Earth, the telecommunications system will be operated at a DC input power level of 26 watts, producing an output RF power of 5 watts, which supports a data return rate from 40 AU of 360 bits per second (70 meter ground station). If three 34 meter antennas are arrayed with a 70 meter antenna, as has been proposed by the NASA Deep Space Network, the rate increases to 470 bits per second.

An energy (not power) management scheme was devised for sciencecraft operation once the craft enters the outer Solar System. This was made necessary by the mismatch between the *input* power requirements of the telecommunications system (26 watts) and the *output* power of the Solar panels (8.5 watts at 40 AU). Thus, during the data playback phase of the mission, a secondary power source (NiCd battery) will be utilized. The Kuiper Express will carry two 300 watt-hour NiCd batteries, one as a fully redundant backup. After the encounter with the Kuiper object, the sciencecraft will spend most of its time charging its battery. For the balance of the time, about four hours out of every twenty-four at 40 AU, the craft will turn on its transmitter and return encounter data to the Earth. Under these conditions, the full complement of encounter data (one gigabit compressed about 3:1 to 350 megabits for downlink) will be returned to the Earth in forty days.

IV. Conclusion

The technological capabilities are now at hand to design an integrated system that combines science instruments, spacecraft, and propulsion elements into a single unit. The authors have named this single unit (and the process used to create it) a *Sciencecraft*. This integration of function allows reduction of cost, mass, and power, with increased science return and reliability. It also supports a shorter development cycle. The reduced mass and size allows the use of smaller, cheaper launch vehicles (e.g., Delta or Poseidon). Reduced electrical power enables the elimination of costly nuclear technology.

V. Acknowledgment

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VII. References

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